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THESIS

STARE CUBESAT COMMUNICATIONS TESTING, SIMULATION AND ANALYSIS

by

Clyde R. Le Gaux III

September 2012

Thesis Advisor: James H. Newman
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13. ABSTRACT (maximum 200 words)

The Space-based Telescope for the Actionable Refinement of Ephemeris (STARE) CubeSat will play an important role in contributing to this nation's space situational awareness (SSA), perhaps one day becoming an integral part of the space surveillance network (SSN) to track orbital debris and satellites, both active and inactive. STARE is a pathfinder mission that is expected to show that CubeSat assets can improve the accuracy of space debris ephemeris data and help national assets avoid conjunction. However, STARE cannot do its job if it cannot communicate effectively with the ground architecture. Knowing the functionality of the on board radio is essential to knowing the capabilities and limitations of the spacecraft. STARE is designed to communicate with the Mobile CubeSat Command and Control (MC3) ground station at the Naval Postgraduate School for data collection and analysis. This thesis shows testing and results, analysis and simulation of the STARE radio and the MC3 ground stations.

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STARE CUBESAT COMMUNICATIONS TESTING, SIMULATION AND ANALYSIS

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Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN SPACE SYSTEMS OPERATIONS

from the

NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

The Space-based Telescope for the Actionable Refinement of Ephemeris (STARE) CubeSat will play an important role in contributing to this nation's space situational awareness (SSA), perhaps one day becoming an integral part of the space surveillance network (SSN) to track orbital debris and satellites, both active and inactive. STARE is a pathfinder mission that is expected to show that CubeSat assets can improve the accuracy of space debris ephemeris data and help national assets avoid conjunction. However, STARE cannot do its job if it cannot communicate effectively with the ground architecture. Knowing the functionality of the on board radio is essential to knowing the capabilities and limitations of the spacecraft. STARE is designed to communicate with the Mobile CubeSat Command and Control (MC3) ground station at the Naval Postgraduate School for data collection and analysis. This thesis shows testing and results, analysis and simulation of the STARE radio and the MC3 ground stations.

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LIST OF ACRONYMS AND ABBREVIATIONS

AFIT	Air Force Institute of Technology
ASAT	Anti-Satellite
Cal_Poly	California Polytechnic State University
CGA	Common Ground Architecture
CIB	Carrier Interface Board
CONOPS	Concept of Operations
CRC	Cycling Redundancy Check
CSLI	CubeSat Launch Initiative
ELaNa	Educational Launch of Nanosatellites
FDITL	First Day In The Life
FEC	Forward Error Correction
FV#	Flight Vehicle #
HAB	High Altitude Balloon
LEO	Low Earth Orbit
MC3	Mobile Cube Sat Command and Control
NPS	Naval Postgraduate School
NRL	Naval Research Laboratories
NRO	National Reconnaissance Office
OUTSat	Operationally Unique Technologies Satellite
PMAD	Power Management And Delivery
P-POD	Poly-Picosatellite Orbital Deployers
RF	Radio Frequency
RSSI	Receive Signal Strength Indication
SSA	Space Situational Awareness
SSN	Space Surveillance Network
STARE	Space-based Telescope for the Actionable Refinement of Ephemeris
STK	Satellite Tool Kit
VPN	Virtual Private Network

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This thesis would not have been possible without the invaluable guidance of my thesis advisors Professor James Newman and CAPT Alan Scott. Without their patience, understanding and encouragement, I would not have been able to succeed at NPS. They allowed me to make mistakes so that I could learn from them and grow as an academic and a professional. To Mr. David Rigmaiden, for putting up with my countless questions and pestering about lab equipment and timelines. I appreciate the hours spent creating the link budget calculation sheet and the hours spent in the lab, completing test after test.

Working with Mrs. Ashley Dittberner and Ms. Madison Studholme made working in the lab a joy and a pleasure. You both put up with my questions and let me tag along on some of your tests. You kept the work environment lighthearted and fun. Ashley’s technical engineer expertise streamlined the testing process and kept everything on track. I truly believe I would not have completed the lab work without you. Madison’s level of knowledge of the STARE program filled many knowledge gaps and she quickly became my go-to person to help me mine out that hard to find information.

Finally, yet importantly, to my beautiful wife and best friend, Heather, who put up with my frustrations and stresses, the late-night study sessions and the educational trips away from home. You kept me grounded throughout this educational experience and always encouraged me when I felt like giving up. To my children, Nicole and Paris, for understanding when Dad could not go out to play because he had homework or studying to do. You never complained or gave me a hard time about it. You two are the best kids a father could ask for. To all my friends, I have acquired during my time at NPS, keep in touch, go out into the world, and accomplish great things.

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I. INTRODUCTION

Space Situational Awareness (SSA) has been a challenge since Sputnik and is an ever-increasing challenge now. Simply put, SSA is the “current and predictive knowledge of space events, threats, activities, conditions, and space system (space, ground link) status, capabilities, constraints and employment—current and future, friendly and hostile—to enable commanders, decision makers, planners, and operators to gain and maintain space superiority across the spectrum of conflict” (HQ Air Force Space Command/A3CD, 2007). Orbital debris has contributed significantly to the SSA problem. Several events in recent history have increased the need for debris tracking and prediction. For example, the collision of an active Iridium 33 communications satellite with an inactive Cosmos 2251 on February 10, 2009, resulted in over 2,000 pieces of man-made orbital debris. Many are too small to be tracked by conventional means (e.g., radar). Figure 1 shows the debris field 180 minutes post-collision. Over time, the debris field has spread out into other orbital planes. Debris also collides with other debris, changing its trajectory and velocity and creating new smaller pieces of debris that further complicates the tracking of these pieces.

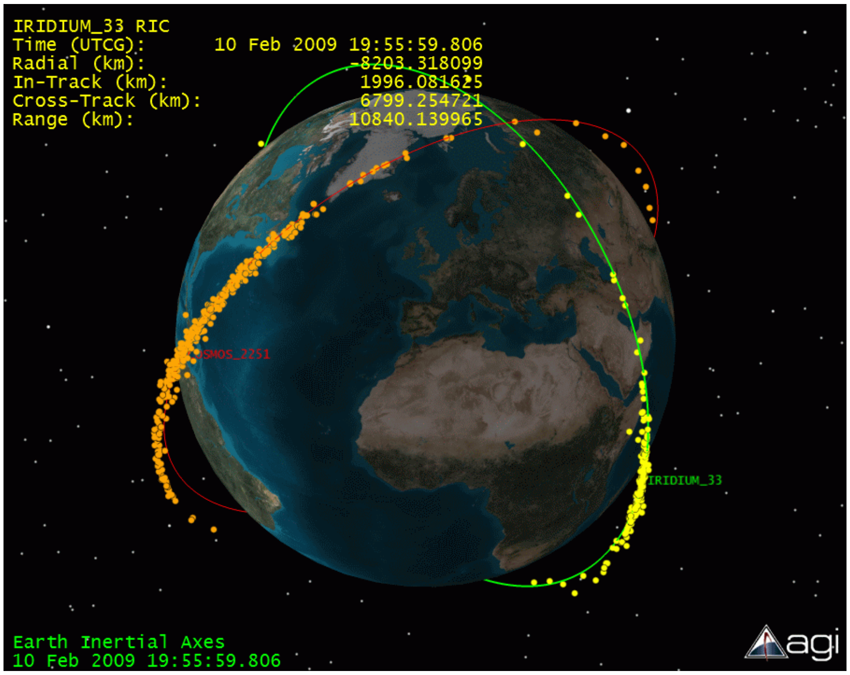

Figure 1. Iridium 33 and Cosmos 2251 Orbits and Debris 180 Minutes Post-Collision (From Kelso, 2009)

Since the space environment, especially Low Earth Orbit (LEO), is increasingly congested, a means to accurately predict the possibility of collision with space debris or other satellites is essential to the safe operation of space assets. The issue of maintaining SSA has garnered international attention and prompted innovative ideas to address the problem. The Space-based Telescope for the Actionable Refinement of Ephemeris (STARE) is one of those innovative ideas. Designed for use in conjunction with the United States Air Force's Space Surveillance Network, a constellation of STARE CubeSats should provide greater fidelity on smaller orbital debris in LEO.

Although quite small, CubeSats may be able to accomplish SSA goals. CubeSats in general have unique communication and data transfer challenges and STARE is no exception. Being in LEO, spacecraft travel at a high velocity and are only overhead for minutes at a time. This short duration creates connection time issues for downloading large amounts of data and uploading commands from a ground station. The size of the spacecraft limits its power

capabilities and the size and type of radio it can carry. This thesis addresses these communication issues through analysis of the STARE CubeSat's link budget.

A. CUBSAT OVERVIEW

CubeSats are the current answer to finding an economical means to deploy experimental spacecraft and conduct research in LEO. The CubeSat form is that of a 10 cm cube that can be stacked to allow room to accommodate the spacecraft bus and payload. As seen in Figure 1, CubeSats come in sizes that range from a 1U to a 3U depending on requirements. These CubeSats have been launched in a variety of small satellite launchers. The STARE CubeSat was integrated into a California Polytechnic State University (Cal_Poly) Poly-Picosatellite Orbital Deployer (P-POD), like the one shown in Figure 2. The P-POD is designed to launch CubeSats using a spring-loaded mechanism.

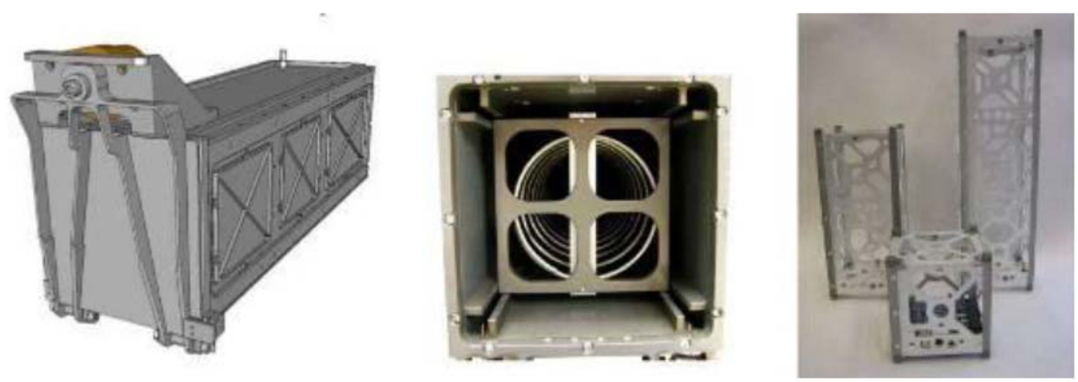

Figure 2. P-POD and CubeSat Structures (1U, 2U, 3U) (From Jerkins, 2010)

B. STARE AND MC3 BACKGROUND

SSA "provides the battlespace awareness required for planning, executing, and assessing protection of space assets, prevention of hostile actions, and negation of hostile resources in all mediums" (HQ Air Force Space Command/A3CD, 2007). Due to events like the COSMOS and Iridium collision,

increased orbital debris has made SSA a major concern for the safety of space assets. Another significant event that contributed to the space debris concern was the Chinese Anti-Satellite (ASAT) test conducted January 19, 2007 that used a direct ascent SC-19 missile against a Fengyun-IC weather satellite that created over 3,000 pieces of orbital debris. As seen in Figure 3, the debris field from the attack has spread to almost every orbital inclination within LEO.

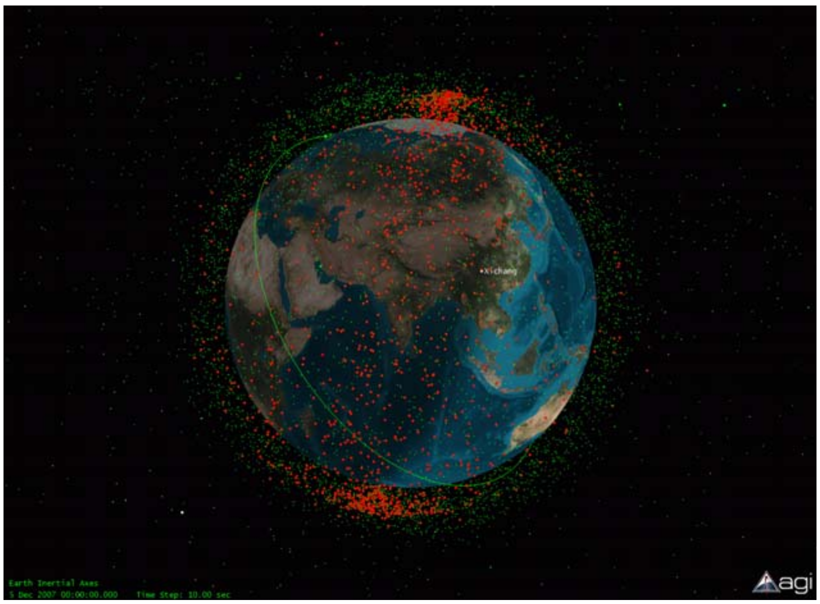

Figure 3. View of ISS Orbit (Green) and Debris Ring (Red) from Chinese ASAT Test (December 5, 2007) (From Kelso, 2011)

STARE was born out of concern over this orbital debris threat. STARE was built by leveraging the Colony Program created by the National Reconnaissance Office (NRO). The idea behind the Colony Program is to advance space technology through the utility and economy of small satellites. The NRO created the Colony I and II buses, seen in Figures 4 and 5, which are designed to be universal platforms for a “plug and play” concept. Universities and government agencies would be able to plug their payload into the universal

Colony bus and send it into space for experimentation and study. The first STARE telescope payload was integrated into a Colony II bus December 21, 2011, at that time for launch on August 2, 2012.

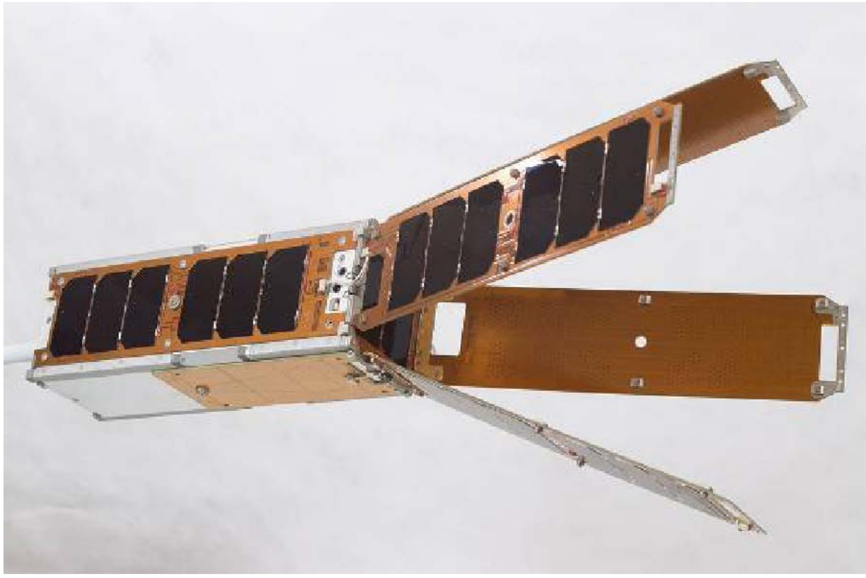

Figure 4. Colony I Bus (From Griffith, 2011)

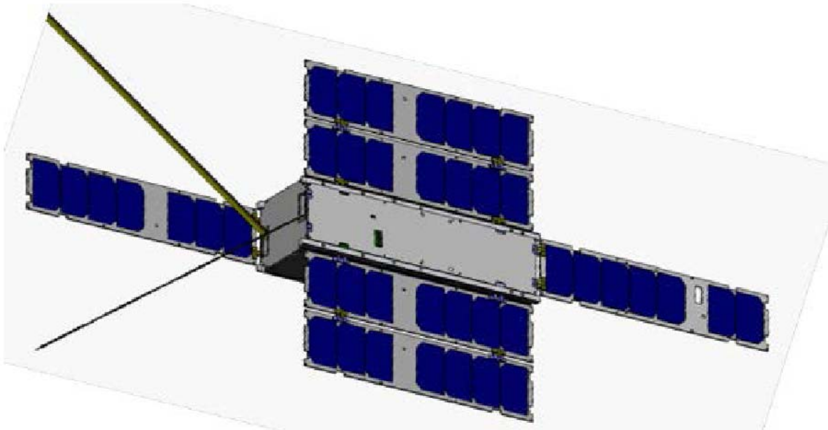

Figure 5. Colony II Bus (From Griffith, 2011)

1. STARE CONOPS

The Concept of Operations (CONOPS) of STARE depicted in Figure 6, shows STARE designed to observe space debris predicted to pass near a space asset and then transmit that image and data to a Mobile CubeSat Command and Control (MC3) ground station, which is discussed in Section 2 of this chapter. This image sent to the MC3 ground station is analyzed to provide a more refined potential conjunction prediction that results in a more informed decision as to whether a space asset must move or not to avoid a collision, and as such, saves fuel and increases the on-orbit lifespan of said spacecraft.

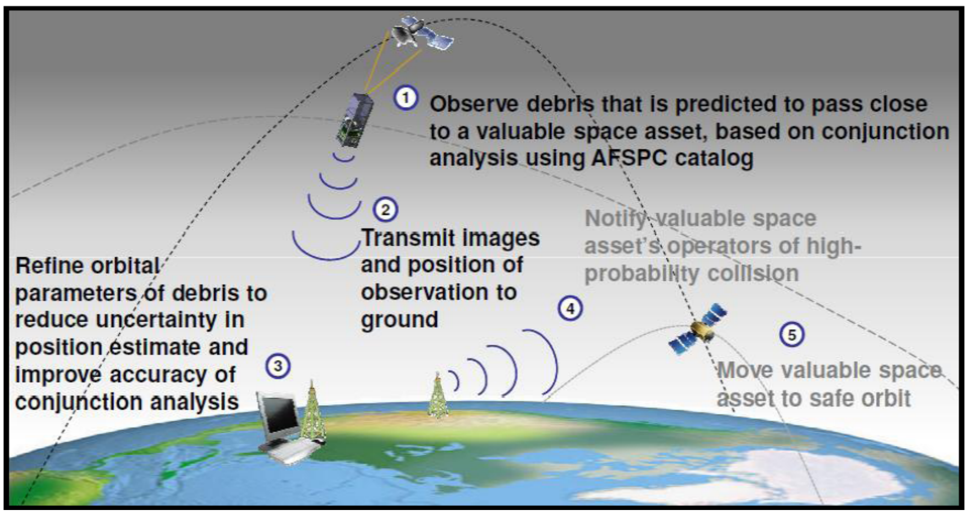

Figure 6. SSA STARE CONOPS (From Simms et al., 2011)

2. MC3 Ground Station

MC3 is a joint project between the Naval Postgraduate School (NPS), the Naval Research Laboratory (NRL), and NRO CubeSat Program Office (QbX) to create an autonomous CubeSat ground station network. The MC3 ground station is designed for use with the NROs Colony II bus. MC3 is also designed to create educational opportunities for university students to conduct research. Universities and government agencies will be able to connect to the network via NPS as the master control station using a Virtual Private Network (VPN) client over the

Internet. Figure 7 shows the MC3 VPN CONOPS. The early MC3 work is documented in theses by Robert C. Griffith entitled “Mobile CubeSat Command and Control (MC3)” and Gregory C. Morrison entitled “Mobile CubeSat Command and Control: Assembly and Lessons Learned.” The current status of MC3 can be found in a thesis by Phillip B. Ibbitson entitled “Mobile CubeSat Command and Control Architecture and CONOPS.”

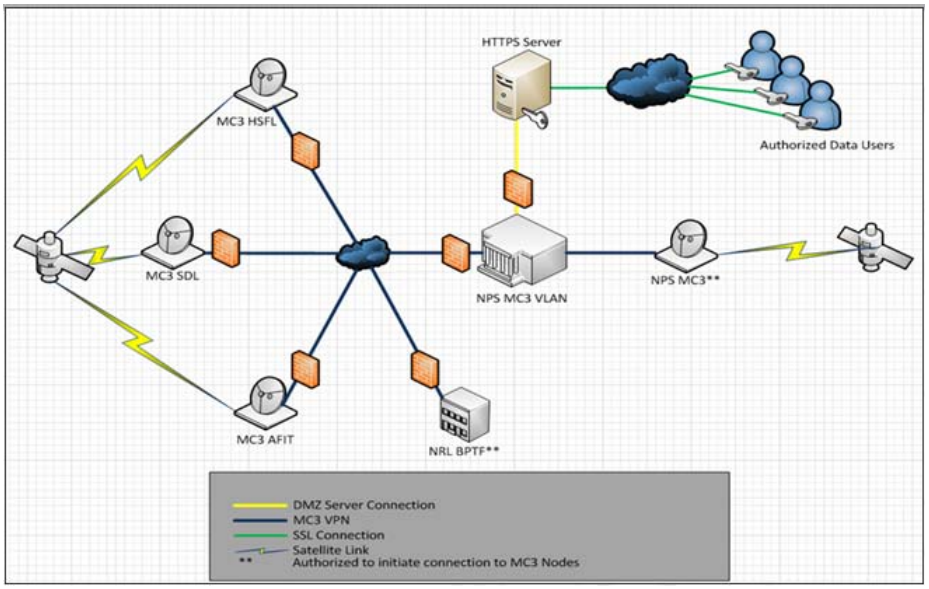

Figure 7. MC3 VPN CONOPS (From CubeSat Workshop Presentation by Minelli, 2012)

a. MC3 Hardware

MC3 is designed to communicate with two CubeSats at once through UHF and S band channels. Each MC3 ground station consists of a rack and antenna set. Each rack and antenna set contains two ICOM 9100 UHF radios for transmitting, two Kantronics KPC 9612+ Terminal Node Controllers (TNC)-a GPS time synchronizer, a two-channel GDP receiver, an S-band up-converter, two Yaesu antenna controllers, four antennas (2 S-band, 2 UHF), a laptop, and a VPN modem. Figures 8 and 9 depict the MC3 rack and antennas.

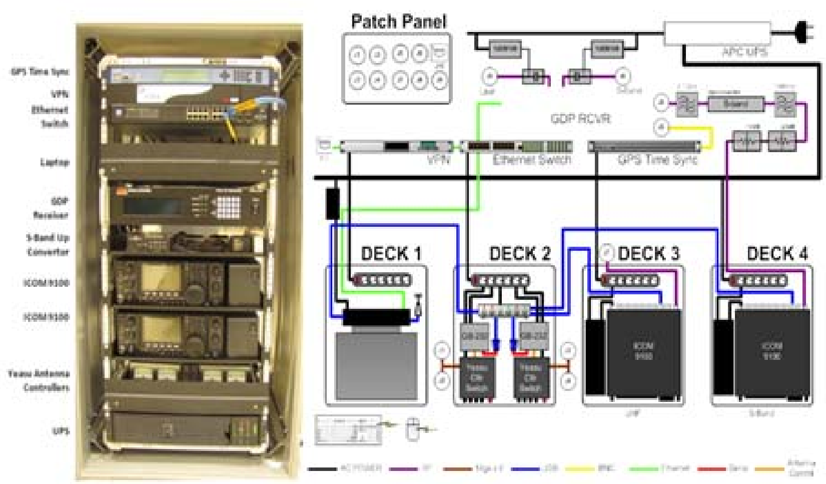

Figure 8. MC3 Rack and Connection Layout (MC3 User Guide)

Figure 9. S band and UHF Antennas

3. STARE Radio

The radio installed on the STARE CubeSat is an AstroDev CII radio, also known as a Kevin Brown radio. This radio was specifically created for use on the Boeing Colony II Bus CubeSats. As stated in the AstroDev CII Product Overview, the radio is designed to receive frequencies from 440–450.5 and 455–462 MHz and a maximum data rate of 9.6 kbps continuous. It uses a GFSK modulation scheme. The transmitter transmits at frequencies between 900–928 MHz and can transmit data at a max rate of 57.6 kbps continuous. The transmitter uses a

BPSK modulation scheme and a nominal operating efficiency of 25 percent. The radios power handling capabilities ranges from 9 to 13 volts at a maximum current of 0.67 amps. The CIIB radio weighs approximately 35 grams and has a tested operating temperature range of -30 to +60 deg C. It has a designed survival temperature range of -40 to +80 deg C. Figure 10 depicts the CII radio with connectors and Figure 11 shows the radio mounted on a Carrier Interface Board (CIB).

Figure 10. CII Radio with RA SMA Connectors (From AstroDev CII Radios: Product Review, 2012)

Figure 11. CII Radio Attached to a CIB (From AstroDev CII Radios: Product Review, 2012)

C. COACH CLASS TO ORBIT

The STARE payload as integrated into the Colony II Bus Flight Vehichle 2 (FV2), also known as Re, will be launched on an ATLAS V rocket on an NRO mission on board a CubeSat launcher developed by NPS called OUTSat. As discussed in a thesis by Adam C. DeJesus entitled “Integration and Environmental Qualification Testing of Spacecraft Structures in Support of the Naval Postgraduate School CubeSat Launcher Program,” OUTSat was specifically designed to meet the weight requirements to be affixed to the upper stage of the ATLAS V rocket. DeJesus coined the phrase “Coach Class to Orbit” as an apt description of the low priority given to secondary payloads and the willingness that CubeSats have to accept harsh conditions to get to space. The first flight of OUTSat is for the OUTSat, the Operationally Unique Technologies Satellite, mission. There are eleven CubeSats being launched.

The NRO has partnered with NASA to fly US Government CubeSats along with CubeSats from universities on NRO launches for the purpose of research and education to further the advancement of small satellite technologies. The NASA CubeSats are part of a NASA program called the Educational Launch of Nanosatellites (ELaNa). Candidates for ELaNa are chosen through NASA’s CubeSat Launch Initiative (CSLI). Four CubeSats from the ELaNa VI program are flying on board OUTSat. OUTSat is affixed to the rear of the upper stage of the Atlas V rocket. It is designed to carry and launch CubeSats from eight P-PODs at one time into orbit. Figure 12 shows a picture of OUTSat after vibration testing and Figure 13 shows OUTSat attached to the aft end of the Atlas V’s Centaur upper stage.

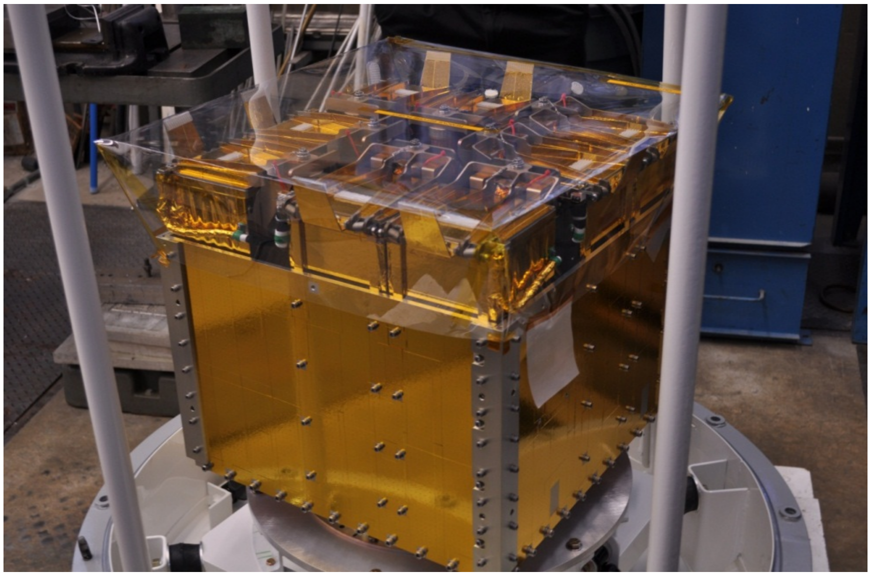

Figure 12. OUTSat CubeSat Launcher

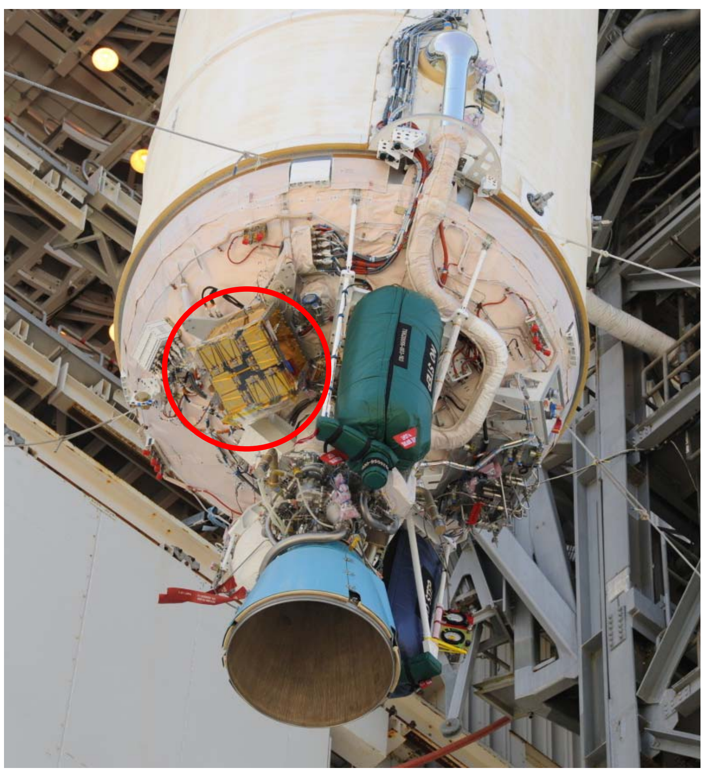

Figure 13. OUTSat Attached to the Upper Stage of the Atlas V Rocket

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II. STARE COMMUNICATIONS

A. RADIO TESTING

A few issues have been identified with the FV2 STARE CubeSat that must be overcome before the MC3 ground stations will be able to communicate routinely with the satellite in orbit. The first issue concerns the spacecraft's batteries. FV2 has two, three cell batteries installed operating at a voltage of about 10 volts. The first battery is labeled "A" while the second battery is labeled "B." Each cell in each battery is numbered one through three. During testing by Boeing, it was discovered that a parasitic load was draining voltage from battery cell A-1 that caused battery B and the two remaining cells in battery A to compensate for the loss. Due to the detected parasitic load in the Power Management and Delivery (PMAD) system, a strong possibility exists that the batteries will not be charged. In other words, by the time the STARE payload in the FV2 CubeSat reaches its intended orbit, the batteries will likely be fully discharged. FV2 upon launch will only have one five-cell solar panel exposed to space, capable of producing a maximum of 5.5 Watts of power. Therefore, that one solar panel is the only source of power available to charge the batteries and power the spacecraft until other solar panels are deployed. The batteries should eventually charge to a level able to power the bus. However, once powered up the bus will drain the battery until it shuts off the bus and the charge cycle must repeat itself.

Deploying the antennas and the solar panels is the second known issue. Once the batteries acquire enough charge to turn on the bus and the spacecraft is "born," a software bug will prevent the solar panels and the radio antennas from deploying. When the spacecraft's bus turns on for the first time, a timer starts that counts down for 45 minutes. Once 45 minutes have expired, the bus will receive an internal command to deploy the solar panels and the radio antennas. The bus will acknowledge the deploy command internally, but due to a software glitch, will deploy neither the solar panels nor the radio antennas. The

software glitch was discovered by Boeing after STARE FV2 was integrated into the P-POD and into OUTSat, when it was too late to update the software. As shown in the antenna port test discussed in Chapter II Section A Part 2, and as shown in Table 1, the Eb/No margins for communicating with STARE are very low with the antennas in the stowed position. But a ground command is the only way to deploy the solar panels and radio antennas.

The last issue concerns the attitude control of STARE. FV2 was originally designed to have reaction wheels that would slew the spacecraft for pointing the payload at space debris, pointing the solar panels at the sun for charging the batteries and pointing nadir for communications with ground stations. During vibration testing of FV1 and FV3, the reaction wheels were damaged, and it was discovered that they would not withstand the harsh vibration environment of the OUTSat launch. Due to this discovery, the spacecraft must rely on the magnetic torque coils, which were originally designed to de-saturate the reaction wheels, for stabilization. Magnetic torque coils produce a magnetic field that reacts with the Earth's geomagnetic field and can be used to control the attitude of the spacecraft. Unfortunately, the attitude control software installed on FV2 is designed to control the reaction wheels for stabilization and slewing but not the magnetic torque coils, which are only used when the spacecraft is in the B-dot damping mode. In B-dot damping mode, the magnetic torque coils are used to slow the spacecraft's rate of tumble. Once the spacecraft's rate of tumble is slow enough, the magnetic torque coils are shut off and the ground station will send a command to the spacecraft to activate the reaction wheels to slew the spacecraft. Since no reaction wheels are installed, the spacecraft will continue to tumble in orbit even if the batteries obtain enough power to start the bus. The spacecraft's uncontrolled tumble will limit the sunlight exposure of the one available solar panel, and as such, prolong the charge time the batteries will require to turn on the bus. A software update is expected to be available to be uploaded to the spacecraft while it is on orbit that will allow the spacecraft to use

the magnetic torque coils for attitude control and slewing. These three issues must be resolved before the MC3 ground stations will be able to communicate normally with STARE in order to perform its mission.

The STARE radio is essential for the spacecraft to receive commands to deploy the antennas, the solar panels, and to maneuver the satellite. Radio testing has been conducted to determine if the MC3 ICOM 9100 UHF radio transmitter at NPS can send out enough energy and if the satellite receive antenna has enough gain to close the communication link and STARE to receive a command. The radio testing was conducted using Flight Vehicle 3 (FV3) as a test platform. Since FV3’s reaction wheels were also damaged during testing, FV3 was reserved as a ground unit to be kept in the FV2 flight configuration for use during FV2’s mission. FV3 has the same radio hardware and firmware installed as FV2. Radio and ground station testing was approached in stages. The first test was the Receive Signal Strength Indication (RSSI) test, next was the Antenna Port test, and last was a High Altitude Balloon (HAB) test.

1. RSSI Test

The RSSI test was designed to determine the minimum signal required for the radio to receive an actual command. The C2B radio is capable of indicating the signal strength that it is receiving from a signal. It gives this information in the form of the RSSI. By finding the threshold where the spacecraft no longer receives a signal and the corresponding RSSI just prior to loss of the signal, NPS was able to determine the minimum signal strength required for the C2B radio to operate. Figures 14 and 15 show the initial coaxial test connection configuration within FV3 and the RSSI test setup.

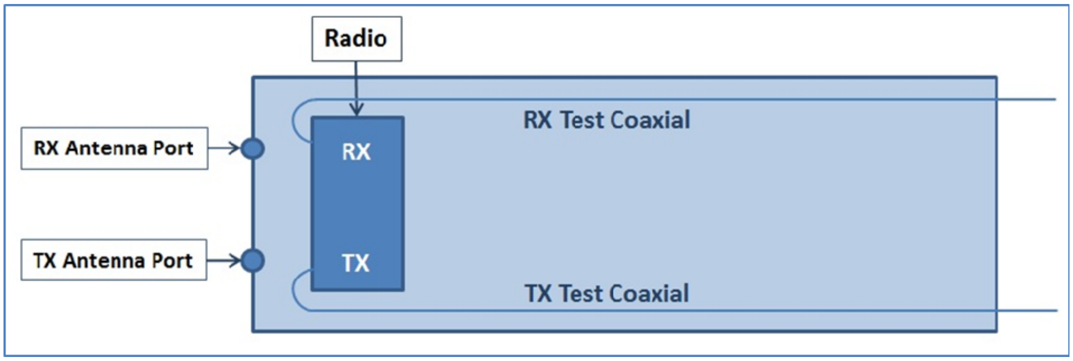

Figure 14. Initial Configuration of the Test Coaxial Cable Locations on FV3 (First Day In The Life (FDITL) of Re and Radio Testing in Preparation for FDITL, 2012)

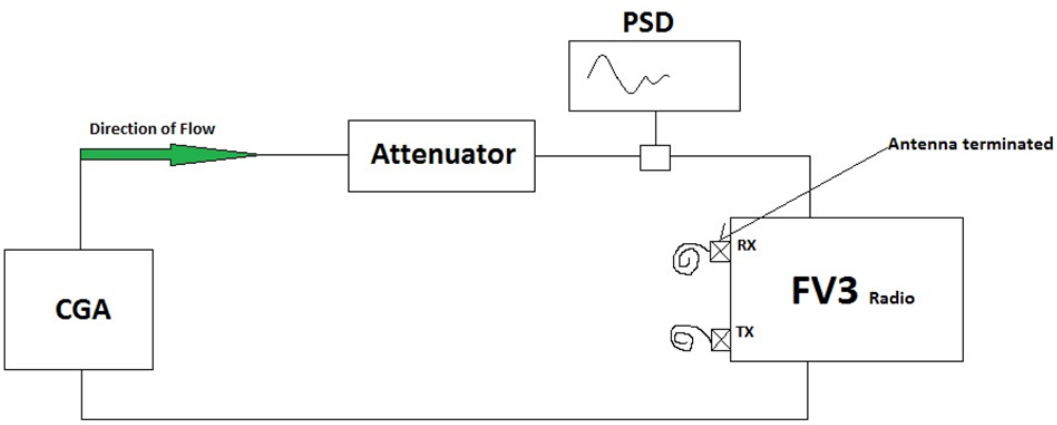

Figure 15. RSSI Test Setup

The FV3 was connected to the ground station using two test coaxial cables installed by Boeing prior to delivery. These cables bypass the antennas for direct Radio Frequency (RF) testing of the radio itself. Using a signal attenuator to decrease signal strength by 10 dB increments, and a spectrum analyzer to see a visual representation of that decrease, it was possible to obtain a ballpark RSSI of 76 to 78 dB of signal strength at an attenuation of 20 dB when telemetry was lost and FV3 would not receive a command signal. The attenuator was then decreased to a setting of 10 dB and next decreased by 1 dB increments to pinpoint at what RSSI signal was lost. The results were at an attenuation between 18 dB and 19 dB, while the RSSI was at 77 dB, when the

signal was lost. This test provided the lower limit of the radio's receive capability, which revealed the dB advantage the ground station must achieve for the radio to receive a transmitted command.

2. Antenna Port Test

The Antenna Port test was conducted to determine the signal strength required for the spacecraft receive antenna to receive transmissions from the ground station while in the stowed configuration on the STARE CubeSat. This test was important to determine if the ground station at NPS would be able to transmit with enough power to close the link with the STARE CubeSat. Figures 16 and 17 show the initial coaxial test connection configuration within FV3 and the setup for the Antenna Port test.

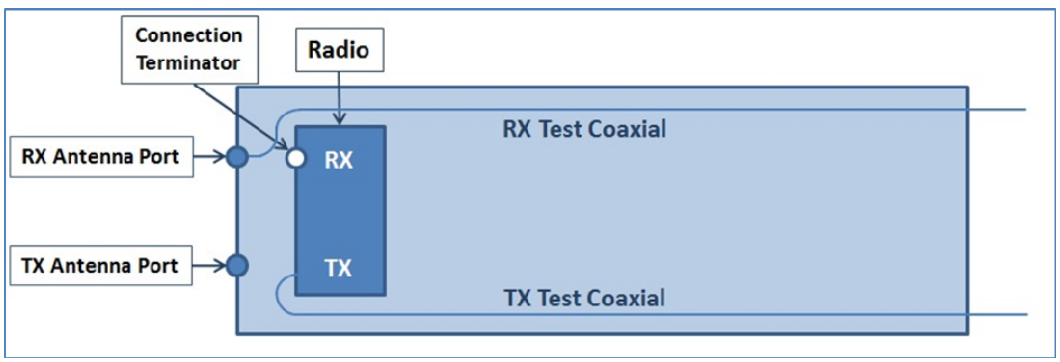

Figure 16. Locations of the Test Coaxial Cables on FV3 During the Antenna Port Test (First Day In The Life (FDITL) of Re and Radio Testing in Preparation for FDITL, 2012)

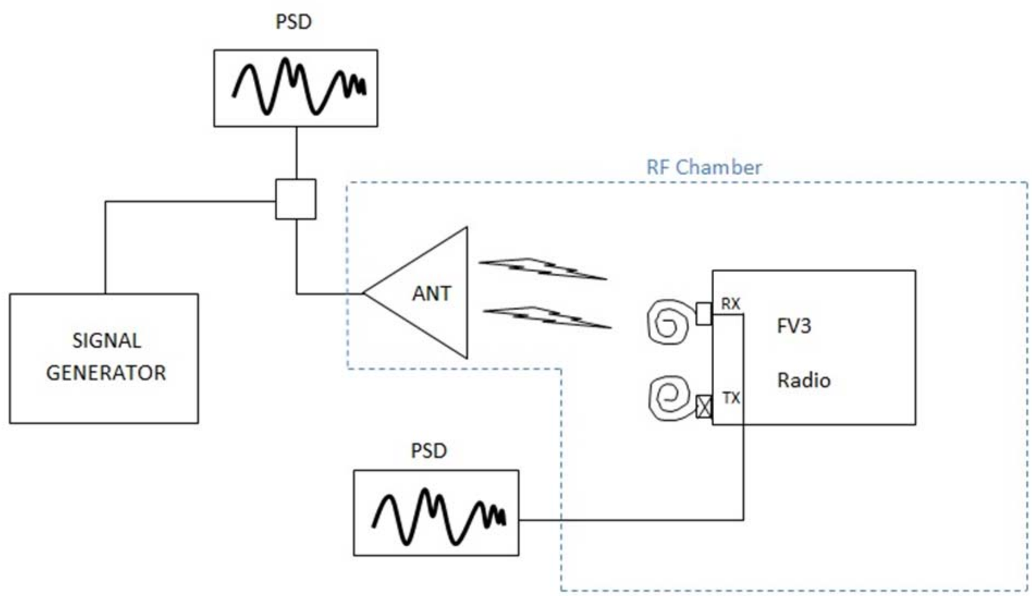

Figure 17. Setup for the Antenna Port Test

The RF chamber in the NPS lab is smaller than required for this test and there was insufficient RF absorbing foam to pad the entire chamber. Due to these conditions, the initial test showed large amounts of transient RF entering the spacecraft. Therefore, the radio was removed from the spacecraft and a special aluminum box was constructed to isolate the radio and antenna set from receiving any transient RF energy from anywhere but the receive antenna. It is impossible to eliminate all transient RF but the aluminum box reduced the transient RF to an almost immeasurable value. Figure 18 depicts the aluminum box set.

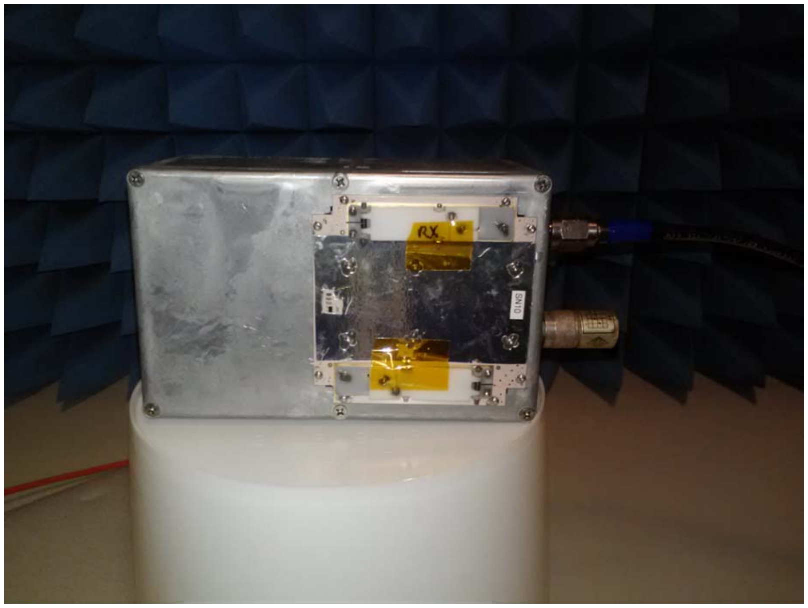

Figure 18. Aluminum Box Radio Setup

Again, the Boeing pre-installed coaxial test cables were used for this test. The receive coaxial cable was removed from the radio's receive port and connected to the receive antenna port. The transmission port was terminated. Using a signal generator and amplifier set, a frequency of 450 MHz with a power of 0 dBm was transmitted into a double-ridged waveguide horn placed exactly one meter from the aluminum box set. This distance allows for measurement of voltage in volts per meter. The system gain measured was -54 dBm using an MXA Signal Analyzer. The unknown value needed was the gain of the stowed antenna. To find the antenna gain value, the other variables had to be eliminated. The gain of the amplifier was 0 dBm, the feed horn gain was 8 dBm, and the path loss was -25.6 dBm; these values were removed from the -54 dBm. Thus, the receive antenna gain equals the gain left over, which is -36.5 dBm. Equations (2-1), (2-2) and (2-3) show the receive antenna gain, Gr, being calculated where Gs is the system gain, Lp is the path loss, Gh is the gain of the feed horn and Ga is the amplifier gain. Having obtained the receive antenna gain value, a link budget calculation sheet was used to extrapolate out to the orbital altitude of the STARE CubeSat. This calculation sheet is shown in Table 1.

$$Gs= Ga + Gh + Lp+ Gr \quad (2\text{-}1)$$

$$Gr= Gs - Lp - Ga - Gh \quad (2\text{-}2)$$

$$Gr=-54\ dBm+25.6\ dBm\ -8\ dBm - 0\ dBm= -36.5\ dBm \quad (2\text{-}3)$$

Item	Units	Down Link			Up Link			
Orbit Altitude	km	500	500	500	500	500	500	
Spacecraft Elevation Angle	deg	10	45	89.99	10	45	89.99	
Frequency	GHz	0.915	0.915	0.915	0.45	0.45	0.45	
Wavelength	m	0.328	0.328	0.328	0.667	0.667	0.667	
Propagation Path Length	km	1695.09	683.09	500.00	1695.09	683.09	500.00	SMAD pg 110-115
Space Loss - L_s	dB	-156.25	-148.36	-145.65	-150.09	-142.20	-139.49	
System Noise Temperature - T_s	k	90	90	90	330	330	330	SMAD pg 556-558
Bit Error Rate		1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05	
Required E_b/N_o for BER 10^{-5}	dB	9.6	9.6	9.6	13.3	13.3	13.3	NSMAD pg 474
Data Rate - R_b	kbps	57.6	57.6	57.6	9.6	9.6	9.6	
Symbols Per Bit		1	1	1	1	1	1	SMAD pg 559
Symbol Rate - R_s	kbps	57.6	57.6	57.6	9.6	9.6	9.6	
ro		1.50	1.50	1.50	1.50	1.50	1.50	
Required C/N_o	dB	57.20	57.20	57.20	53.12	53.12	53.12	E_b/N_o+10*log(R_b)
Bandwidth - BW	MHz	0.144	0.144	0.144	0.024	0.024	0.024	(1+ro)*R_s
Required C/N	dB	5.62	5.62	5.62	9.32	9.32	9.32	C/N_o-10*log(BW)
Receiver Bandwidth - B	MHz	0.2	0.2	0.2	0.2	0.2	0.2	
GND Antenna Diameter	m	0.88	0.88	0.88	1.27	1.27	1.27	
GND Antenna Feed Efficiency	%	100	100	100	100	100	100	
GND Antenna Half Power Beamwidth	deg	26.08	26.08	26.08	36.75	36.75	36.75	SMAD pg 571
GND Antenna Pointing Error	deg	2.0	2.0	2.0	2.0	2.0	2.0	
GND Antenna Pointing Error Loss - L_θ	dB	-1.24	-1.24	-1.24	-0.90	-0.90	-0.90	
GND Antenna Gain - G	dBi	18.52	18.52	18.52	15.54	15.54	15.54	
S/C Antenna Diameter	m	0.118	0.118	0.118	0.24	0.24	0.24	
S/C Antenna Feed Efficiency	%	100	100	100	0.022	0.022	0.022	
S/C Antenna Half Power Beamwidth	deg	70.00	70.00	70.00	70.00	70.00	70.00	SMAD pg 571
S/C Antenna Pointing Error	deg	10.0	10.0	10.0	10.0	10.0	10.0	
S/C Antenna Pointing Error Loss - L_θ	dB	-2.18	-2.18	-2.18	-2.18	-2.18	-2.18	
S/C Antenna Gain - G	dBi	1.07	1.07	1.07	1.07	1.07	1.07	
Transmitter Power	Watts	2	2	2	75	75	75	
Transmitter Power - P	dBW	3.01	3.01	3.01	18.75	18.75	18.75	
Transmitter Line Loss - L_l	dB	-0.5	-0.5	-0.5	-4	-4	-4	
Transmitter Feed Loss - L_t	dB	0.00	0.00	0.00	0.00	0.00	0.00	
Transmitter EIRP	dBW	3.58	3.58	3.58	30.29	30.29	30.29	EIRP=P+L_l+G_t+L_t
Transmission Path Losses - L_a	dB	-0.50	-0.50	-0.50	-0.50	-0.50	-0.50	
Receiver Polarization Loss - L_p	dB	-3	-3	-3	-3	-3	-3	
Receiver Line Loss - L_l	dB	-1	-1	-1	-0.5	-0.5	-0.5	
Receiver Feed Loss - L_r	dB	0.00	0.00	0.00	-36.58	-36.58	-36.58	
Received Carrier Power - C	dBW	-142.08	-134.19	-131.48	-162.39	-154.49	-151.78	C=EIRP+L_s+L_a+G
Total Received Noise Power - N	dB	-156.05	-156.05	-156.05	-150.41	-150.41	-150.41	N=k*T_s*B k=1.38E-23
Received Carrier To Noise Ratio - C/N	dB	13.97	21.86	24.57	-11.98	-4.09	-1.38	SMAD pg 550-556
Received Energy Per Bit - E_b	dB	-189.68	-181.79	-179.08	-202.21	-194.31	-191.60	E_b=C/R_s
Received Noise Spectral Density - N_o	dB	-209.06	-209.06	-209.06	-203.42	-203.42	-203.42	N_o=k*T_s
Calculated Eb/No	dB	19.37	27.27	29.98	1.21	9.10	11.81	
Eb/No Margine	dB	9.77	17.67	20.38	-12.09	-4.20	-1.49	

Table 1. STARE Antenna Stowed Link Budget 2012

Due to the receive antenna being in the stowed configuration, the -36.5 dB gain equates to a loss in the antenna's feed efficiency. By lowering the antenna feed efficiency to .022 percent in the calculation sheet, the -36.5 dB antenna gain is seen in the receiver feed loss of the radio. This negates the antenna and shows the -36 dB gain at the radio and reveals the calculated Eb/No margin from

the NPS transmitter set to STARE. As seen in the table, with the spacecraft on a direct overhead pass of the NPS ground station, the NPS transmission can only produce a maximum Eb/No of -1.49 dB. Since the gain of the stowed antenna is -36.5 dB, there is insufficient Eb/No margin to close the link with STARE using the NPS ground station transmitter. The margin is close at -1.49 dB and there is a weak possibility of success, but while the spacecraft is in orbit, NPS will continue to attempt contact with the STARE spacecraft as the opportunity presents itself.

a. SRI

The NPS Yagi antenna does not have the gain required to complete the communications link with the STARE spacecraft with the receive antenna in the stowed configuration. A possible solution to the gain problem is to use a different antenna. The 60 ft antenna at SRI located in the foothills above SRI International near Stanford, CA has an advertised gain of 35 dB. By connecting NPS's amplifier and transmitter to SRI's antenna, the Eb/No margin increases from -1.49 dB to 11.67 dB for a direct overhead pass that allows for a greater chance that STARE will be able to receive a command. There is only a 13 dB Eb/No margin increase over the NPS Yagi antenna because the SRI antenna's half power beam width is 2.55 degrees while the Yagi antenna's half power beam width is 36.75 degrees. This difference in half power beam width creates a significant difference in pointing error loss. The pointing error loss for the SRI antenna is - 8.19 dB while the Yagi antenna's pointing error loss is -2.18 dB. In addition, the feed efficiency of the SRI antenna is less than half of the Yagi's, but with the increased gain of the SRI antenna the losses are overcome. Table 2 contains the SRI link budget. Figure 19 is a photo of the SRI dish.

Figure 19. SRI 60 ft Antenna Dish

Item	Units	Down Link				Up Link					
Orbit Altitude	km	500	500	500		500	500	500			
Spacecraft Elevation Angle	deg	10	45	89.99		10	45	89.99			
Frequency	GHz	0.915	0.915	0.915		0.45	0.45	0.45			
Wavelength	m	0.328	0.328	0.328		0.667	0.667	0.667			
Propagation Path Length	km	1695.09	683.09	500.00		1695.09	683.09	500.00	SMAD pg 110-115		
Space Loss - L_s	dB	-156.25	-148.36	-145.65		-150.09	-142.20	-139.49			
System Noise Temperature - T_s	k	90	90	90		330	330	330	SMAD pg 556-558		
Bit Error Rate		1.00E-05	1.00E-05	1.00E-05		1.00E-05	1.00E-05	1.00E-05			
Required E_b/N_o for BER 10^{-5}	dB	9.6	9.6	9.6		13.3	13.3	13.3	NSMAD pg 474		
Data Rate - R_b	kbps	57.6	57.6	57.6		9.6	9.6	9.6			
Symbols Per Bit		1	1	1		1	1	1	SMAD pg 559		
Symbol Rate - R_s	kbps	57.6	57.6	57.6		9.6	9.6	9.6			
ro		1.50	1.50	1.50		1.50	1.50	1.50			
Required C/N_o	dB	57.20	57.20	57.20		53.12	53.12	53.12	E_b/N_o+10*log(R_b)		
Bandwidth - BW	MHz	0.144	0.144	0.144		0.024	0.024	0.024	(1+ro)*R_s		
Required C/N	dB	5.62	5.62	5.62		9.32	9.32	9.32	C/N_o-10*log(BW)		
Receiver Bandwidth - B	MHz	0.2	0.2	0.2		0.2	0.2	0.2			
GND Antenna Diameter	m	0.88	0.88	0.88		18.288	18.288	18.288	SRI 60ft Dish 35 dB gain		
GND Antenna Feed Efficiency	%	100	100	100		42.5	42.5	42.5			
GND Antenna Half Power Beamwidth	deg	26.08	26.08	26.08		2.55	2.55	2.55	SMAD pg 571		
GND Antenna Pointing Error	deg	2.0	2.0	2.0		2.0	2.0	2.0			
GND Antenna Pointing Error Loss - L_θ	dB	-1.24	-1.24	-1.24		-8.19	-8.19	-8.19			
GND Antenna Gain - G	dBi	18.52	18.52	18.52		38.71	38.71	38.71			
S/C Antenna Diameter	m	0.118	0.118	0.118		0.24	0.24	0.24			
S/C Antenna Feed Efficiency	%	100	100	100		0.022	0.022	0.022			
S/C Antenna Half Power Beamwidth	deg	70.00	70.00	70.00		70.00	70.00	70.00	SMAD pg 571		
S/C Antenna Pointing Error	deg	10.0	10.0	10.0		10.0	10.0	10.0			
S/C Antenna Pointing Error Loss - L_θ	dB	-2.18	-2.18	-2.18		-2.18	-2.18	-2.18			
S/C Antenna Gain - G	dBi	1.07	1.07	1.07		1.07	1.07	1.07			
Transmitter Power	Watts	2	2	2		75	75	75			
Transmitter Power - P	dBW	3.01	3.01	3.01		18.75	18.75	18.75			
Transmitter Line Loss - L_l	dB	-0.5	-0.5	-0.5		-3	-3	-3			
Transmitter Feed Loss - L_θ	dB	0.00	0.00	0.00		-3.72	-3.72	-3.72			
Transmitter EIRP	dBW	3.58	3.58	3.58		50.74	50.74	50.74	EIRP=P+L_l+G_t+L_θ		
Transmission Path Losses - L_a	dB	-0.50	-0.50	-0.50		-0.50	-0.50	-0.50			
Receiver Polarization Loss - L_a	dB	-3	-3	-3		-3	-3	-3			
Receiver Line Loss - L_a	dB	-1	-1	-1		-0.5	-0.5	-0.5			
Receiver Feed Loss - L_a	dB	0.00	0.00	0.00		-36.58	-36.58	-36.58			
Received Carrier Power - C	dBW	-142.08	-134.19	-131.48		-149.23	-141.33	-138.62	C=EIRP+L_s+L_a+G		
Total Received Noise Power - N	dB	-156.05	-156.05	-156.05		-150.41	-150.41	-150.41	N=k*T_s*B k=1.38E-23		
Received Carrier To Noise Ratio - C/N	dB	13.97	21.86	24.57		1.18	9.07	11.78	SMAD pg 550-556		
Received Energy Per Bit - E_b	dB	-189.68	-181.79	-179.08		-189.05	-181.16	-178.45	E_b=C/R_s		
Received Noise Spectral Density - N_o	dB	-209.06	-209.06	-209.06		-203.42	-203.42	-203.42	N_o=k*T_s		
Calculated Eb/No	dB	19.37	27.27	29.98		14.37	22.26	24.97			
Eb/No Margins	dB	9.77	17.67	20.38		1.07	8.96	11.67			

Table 2. STARE SRI Link Budget

3. High Altitude Balloon Test (HAB)

To validate that the NPS ground station can track a radio beacon, a HAB test was performed June 29, 2012 using a custom-built CalPoly beacon. In preparation for the actual balloon launch, the radio beacon was tested in the NPS lab. For this testing, the radio was walked around the NPS campus being tracked by the NPS ground station to verify the radio beacon was transmitting and to verify the NPS ground station could track the radio. The balloon and payload

were driven to and released from Vosti Park in Soledad, CA. Figure 20 shows the balloon and payload ready for launch. Figure 21 shows the balloon and payload ascending minutes after release.

Figure 20. Balloon and Payload Ready for launch (NPS Laboratory Manager David Rigmaiden Prepares to Release the Balloon and Payload)

Figure 21. Balloon and Payload on Ascent

The NPS ground station first detected and received a transmission beacon at 437 MHz from the Cal_Poly beacon at 11:01:46am 33 miles away at an altitude of 1,831 meters. The balloon reached a maximum altitude of 22,267 meters with an average ascent rate of 147.4 meters per minute before it burst. The payload made a rapid decent and landed in a field 75.7 miles from NPS just east of Interstate 5 and situated in a latitude between Fresno and Modesto, CA. Figures 22 and 23 show the landing site and the condition of the payload after landing.

Figure 22. Payload and Parachute After landing

Figure 23. Payload Condition Picture

The total duration of the flight from initial tracking to landing was two hours 28 minutes and 19 seconds. During the launch, one chase vehicle was positioned at the anticipated landing point. Software was used to predict the landing point based on the anticipated winds on the launch day. Another chase vehicle left 30 minutes after launch from Soledad and tracked the payload using a mobile receiver set. The second chase vehicle was able to maintain a good receive signal through the entire chase. A SPOT GPS receiver/transmitter was

used to track the exact location of the payload as it ascended and descended. The SPOT transmitter gave the exact latitude and longitude of the payload throughout the test. A link budget was created using the data retrieved from the HAB test to obtain the downlink Eb/No margin value achieved at the maximum altitude reached by the payload. The maximum altitude achieved was 22.3 km with a look angle of 11.5 degrees and a maximum slant range of 111.5 km from the NPS ground station. As shown in Table 2, the maximum downlink Eb/No margin achieved at that altitude and look angle was 27.94 dB that equates to great communications from the HAB radio beacon to the ground receiver at NPS. Table 3 shows the HAB downlink calculations. Utilizing the same 11.5 degree elevation angle and the 437 MHz frequency from the HAB test but inserting the STARE orbital altitude into the calculation sheet, the Eb/No margin decreases to 4.72 dB as shown in Table 4. This Eb/No margin would still be sufficient for the NPS ground station to receive a signal from STARE but the margin decrease is very large due to the frequency used. Using the anticipated STARE orbital altitude and the downlink frequency of 915 MHz in the link budget calculation sheet with the 11.5 degree elevation angle gives an Eb/No margin of 10.28 dB. This test showed the NPS ground station hardware and software were able to sufficiently track the HAB payload and received beaconing data from it at a high altitude. This test also gives an idea of the downlink communications characteristics expected between the STARE spacecraft on orbit and the NPS ground station.

Item	Units	Down Link		
Orbit Altitude	km	22.3		
Spacecraft Elevation Angle	deg	11.5		
Frequency	GHz	0.437		
Wavelength	m	0.686		
Propagation Path Length	km	107.50		
Space Loss - L_s	dB	-125.88	SMAD pg 110-115	
System Noise Temperature - T_s	k	90		
Bit Error Rate		1.00E-05	SMAD pg 556-558	
Required E_b/N_o for BER 10^{-5}	dB	9.6		
Data Rate - R_b	kbps	57.6	NSMAD pg 474	
Symbols Per Bit		1		
Symbol Rate - R_s	kbps	57.6	SMAD pg 559	
ro		1.50		
Required C/N_o	dB	57.20		
Bandwidth - BW	MHz	0.144	E_b/N_o+10*log(R_b)	
Required C/N	dB	5.62	(1+ro)*R_s	
Receiver Bandwidth - B	MHz	0.2	C/N_o-10*log(BW)	
GND Antenna Diameter	m	0.88		
GND Antenna Feed Efficiency	%	100		
GND Antenna Half Power Beamwidth	deg	54.61		
GND Antenna Pointing Error	deg	2.0	SMAD pg 571	
GND Antenna Pointing Error Loss - L_s	dB	-0.61		
GND Antenna Gain - G	dBi	12.10		
S/C Antenna Diameter	m	0.118		
S/C Antenna Feed Efficiency	%	100		
S/C Antenna Half Power Beamwidth	deg	70.00		
S/C Antenna Pointing Error	deg	10.0	SMAD pg 571	
S/C Antenna Pointing Error Loss - L_s	dB	-2.18		
S/C Antenna Gain - G	dBi	-5.35		
Transmitter Power	Watts	2		
Transmitter Power - P	dBW	3.01		
Transmitter Line Loss - L_l	dB	-0.5		
Transmitter Feed Loss - L_s	dB	0.00		
Transmitter EIRP	dBW	-2.84		
Transmission Path Losses - L_s	dB	-0.50	EIRP=P+L_l+G_s+L_s	
Receiver Polarization Loss - L_s	dB	-3		
Receiver Line Loss - L_s	dB	-1		
Receiver Feed Loss - L_s	dB	0.00		
Received Carrier Power - C	dBW	-123.92		
Total Received Noise Power - N	dB	-156.05	C=EIRP+L_s+L_s+G	
Received Carrier To Noise Ratio - C/N	dB	32.13	N=k*T_s*B	k=1.38E-23
Received Energy Per Bit - E_b	dB	-171.52	SMAD pg 550-556	
Received Noise Spectral Density - N_o	dB	-209.06	E_b=C/R_s	
Calculated Eb/No	dB	37.54	N_o=k*T_s	
Eb/No Margine	dB	27.94		

Table 3. HAB Link Budget 2012

Item	Units	Down Link		
Orbit Altitude	km	500		
Spacecraft Elevation Angle	deg	11.5		
Frequency	GHz	0.437		
Wavelength	m	0.686		
Propagation Path Length	km	1599.83		
Space Loss - L_s	dB	-149.33	SMAD pg 110-115	
System Noise Temperature - T_s	k	90		
Bit Error Rate		1.00E-05	SMAD pg 556-558	
Required E_b/N_o for BER 10^{-5}	dB	9.6		
Data Rate - R_b	kbps	57.6	NSMAD pg 474	
Symbols Per Bit		1		
Symbol Rate - R_s	kbps	57.6	SMAD pg 559	
ro		1.50		
Required C/N_o	dB	57.20		
Bandwidth - BW	MHz	0.144	E_b/N_o+10*log(R_b)	
Required C/N	dB	5.62	(1+ro)*R_s	
Receiver Bandwidth - B	MHz	0.2	C/N_o-10*log(BW)	
GND Antenna Diameter	m	0.88		
GND Antenna Feed Efficiency	%	100		
GND Antenna Half Power Beamwidth	deg	54.61		
GND Antenna Pointing Error	deg	2.0	SMAD pg 571	
GND Antenna Pointing Error Loss - L_s	dB	-0.61		
GND Antenna Gain - G	dBi	12.10		
S/C Antenna Diameter	m	0.118		
S/C Antenna Feed Efficiency	%	100		
S/C Antenna Half Power Beamwidth	deg	70.00		
S/C Antenna Pointing Error	deg	10.0	SMAD pg 571	
S/C Antenna Pointing Error Loss - L_s	dB	-2.18		
S/C Antenna Gain - G	dBi	-5.35		
Transmitter Power	Watts	2		
Transmitter Power - P	dBW	3.01		
Transmitter Line Loss - L_l	dB	-0.5		
Transmitter Feed Loss - L_s	dB	0.00		
Transmitter EIRP	dBW	-2.84		
Transmission Path Losses - L_s	dB	-0.50	EIRP=P+L_l+G_s+L_s	
Receiver Polarization Loss - L_s	dB	-3		
Receiver Line Loss - L_s	dB	-1		
Receiver Feed Loss - L_s	dB	0.00		
Received Carrier Power - C	dBW	-147.37		
Total Received Noise Power - N	dB	-156.05	C=EIRP+L_s+L_s+G	
Received Carrier To Noise Ratio - C/N	dB	8.68	N=k*T_s*B	k=1.38E-23
Received Energy Per Bit - E_b	dB	-194.98	SMAD pg 550-556	
Received Noise Spectral Density - N_o	dB	-209.06	E_b=C/R_s	
Calculated Eb/No	dB	14.08	N_o=k*T_s	
Eb/No Margine	dB	4.48		

Table 4. HAB Link Budget using STARE Orbital Altitude

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III. GROUND ARCHITECTURE DESIGN

A. MC3 GROUND STATIONS

The ground architecture of any space program is arguably just as important as the spacecraft itself. Many constraints exist, such as funding, available land, and spacecraft orbital parameters that limit where and how many ground stations can and should be erected. The MC3 program is no exception. As of September 2012, four university MC3 ground stations are located across the Unites States. The first ground station was installed on top of Spanagel Hall on the NPS campus located at 36.5944444 deg N, 121.875 deg W. The second ground station was installed at the Air Force Institute of Technology (AFIT) on Wright-Patterson Air Force Base in Ohio located at 39.781981 deg N, 84.082206 deg W. The third ground station was installed at the Space Dynamics Laboratory in Logan, Utah next to Utah State University at 41.76073 deg N, 111.81942 deg W. The fourth ground station was installed at the University of Hawaii Manoa at 21.299 deg N, 157.816 deg W. Figure 24 shows a Satellite Tool Kit (STK) representation of MC3 ground station placement.

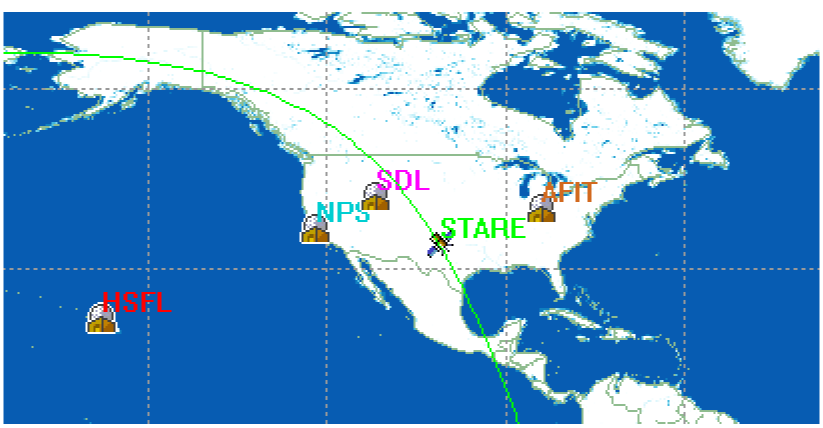

Figure 24. STK MC3 Ground Station Locations

B. MC3 GROUND STATION ACCESS TO STARE

Assuming the issues discussed in Chapter II are resolved, Table 5 shows the ground stations will have adequate Eb/No margin to close the link with a fully operational STARE CubeSat, with the highest Eb/No margins occurring when STARE is at an elevation angle from the ground stations between 45 degrees and 90 degrees. If the spacecraft antennas fail to deploy and remain in the stowed configuration, as shown in Table 1, an elevation angle between 45 degrees and 90 degrees also gives the highest Eb/No margin for the NPS ground station to attempt to close the link with STARE. Therefore, these elevation angle limits were used in the access analysis to see how many opportunities the NPS ground station would have to try to communicate with STARE on orbit

1. MC3 First Look at 10 Degrees Elevation Angle

STARE is scheduled to be released from OUTSat three hours after launch of the Atlas V rocket from Vandenberg Air Force Base into an orbit of 450 km x 650km with a 66-degree inclination. With the issue of non-deployment of the STARE antennas a factor, an analysis and simulation of the STARE CubeSat was conducted using the Satellite Tool Kit (STK) developed by AGI to see when the NPS ground station site would get its first look at STARE on orbit. A constraint of 10 degrees elevation angle above the horizon was used in the analysis. This analysis was conducted over a one-year timeframe from the initial scheduled launch date of August 2, 2012. Table 5 shows the results.

First Look NPS to STARE (10 degree Elevation Angle)			
Average Duration	389.86	seconds	
Maximum Duration	546.551	seconds	
Minimum Duration	10.956	seconds	
Total Passes for a Year	1322	passes	

Table 5. 10 Degree Elevation Angle First Look Analysis

The analysis shows 1,322 opportunities NPS would have to communicate with STARE. Given STARE's Operational Link Budget, shown in Table 6, the average pass duration of 390 seconds would allow the NPS MC3 ground station plenty of time to upload a command sequence. Each command sequence can contain several commands in one transmission. Each command in the sequence consists of a different amount of bytes. For example, a command sequence of:

- Point = 200 bytes
- Turn on Payload = 50 bytes
- Get Payload Temperature = 150 Bytes
- Get Payload GPS Fix = 150 Bytes
- Get Image = 150 bytes
- Sun Soak = 200 bytes
- Turn Off Payload = 50 bytes

This theoretical command sequence would total almost 1,000 bytes. Since there are 8 bits in a byte, the total command sequence is 8,000 bits. Each command message in the command sequence has a message header that is 8 bytes plus a Cycling Redundancy Check (CRC) that consists of 2 bytes These message segments combine to equal a message overhead of 80 bits per command. Since a sequence consists of seven commands, 560 bits must be added to the sequence total, yielding 8,560 bits. Now, each message is encrypted with AES 256-Bit encryption equaling 15 bytes per message adds another message overhead of 840 bits per message that is added to the sequence total yielding 9400 bits. Each message packet has an open flag and a close flag consisting of a 7E hexadecimal each. These flags let the spacecraft know when a message starts and when it ends. Each flag is 1 byte each, therefore, 16 bits per message is added to the command sequence producing a total of 9512 bits. Since MC3's uplink data rate is 9600 bits per second, it would

only take approximately 1 second to uplink the total command sequence to the STARE radio (Naval Research Laboratory Interface Control Document (ICD), 2011).

The downloading of data from STARE with an average duration time of 390 seconds takes longer but is achievable in one pass or two passes depending on the size of the data transmitted. As discussed in a thesis written by Tolulope E. O'Brien entitled "Space Situational Awareness Cube Sat Concept of Operations" the raw image data collected by STARE is an average size of 600 to 700 kB after compression for transmission and the processed image data is approximately 1,088 bytes. The raw data is so large due to the image containing noise and sky background data. Just as the uplink command sequence has overhead data, so does the downlink data. Each data transmission contains GPS data at 645 bytes, telemetry data, and a 12-byte header. This data along with the raw image data is stored aboard the spacecraft on a 2 GB SD card at a particular time interval. O'Brien used a conservative storage rate of 60 seconds and 10 processed images and one raw image. The data for a day, as shown in Table 7, would be 2.20 MB. If FEC is used the overhead will be 33 percent more which adds 5,808 kb. The STARE radio has a downlink data rate of 57.6 kb per second. Converting 2.20 MB to bits equals 17,600 kb and adding 5,808 kb, the total is 23,408 kb. At 57.6 kb per second downlink rate, it would take 406.4 seconds to down load the data to MC3.

Item	Units	Down Link				Up Link				
Orbit Altitude	km	500	500	500		500	500	500		
Spacecraft Elevation Angle	deg	10	45	89.99		10	45	89.99		
Frequency	GHz	0.915	0.915	0.915		0.45	0.45	0.45		
Wavelength	m	0.328	0.328	0.328		0.667	0.667	0.667		
Propagation Path Length	km	1695.09	683.09	500.00		1695.09	683.09	500.00	SMAD pg 110-115	
Space Loss - L_s	dB	-156.25	-148.36	-145.65		-150.09	-142.20	-139.49		
System Noise Temperature - T_s	k	90	90	90		330	330	330	SMAD pg 556-558	
Bit Error Rate		1.00E-05	1.00E-05	1.00E-05		1.00E-05	1.00E-05	1.00E-05		
Required E_b/N_o for BER 10^{-5}	dB	9.6	9.6	9.6		13.3	13.3	13.3	NSMAD pg 474	
Data Rate - R_b	kbps	57.6	57.6	57.6		9.6	9.6	9.6		
Symbols Per Bit		1	1	1		1	1	1	SMAD pg 559	
Symbol Rate - R_s	kbps	57.6	57.6	57.6		9.6	9.6	9.6		
ro		1.50	1.50	1.50		1.50	1.50	1.50		
Required C/N_o	dB	57.20	57.20	57.20		53.12	53.12	53.12	$E_b/N_o+10*\log(R_b)$	
Bandwidth - BW	MHz	0.144	0.144	0.144		0.024	0.024	0.024	$(1+ro)*R_s$	
Required C/N	dB	5.62	5.62	5.62		9.32	9.32	9.32	$C/N_o-10*\log(BW)$	
Receiver Bandwidth - B	MHz	0.2	0.2	0.2		0.2	0.2	0.2		
GND Antenna Diameter	m	0.88	0.88	0.88		1.27	1.27	1.27		
GND Antenna Feed Efficiency	%	100	100	100		100	100	100		
GND Antenna Half Power Beamwidth	deg	26.08	26.08	26.08		36.75	36.75	36.75	SMAD pg 571	
GND Antenna Pointing Error	deg	2.0	2.0	2.0		2.0	2.0	2.0		
GND Antenna Pointing Error Loss - L_θ	dB	-1.24	-1.24	-1.24		-0.90	-0.90	-0.90		
GND Antenna Gain - G	dBI	18.52	18.52	18.52		15.54	15.54	15.54		
S/C Antenna Diameter	m	0.118	0.118	0.118		0.24	0.24	0.24		
S/C Antenna Feed Efficiency	%	100	100	100		100	100	100		
S/C Antenna Half Power Beamwidth	deg	70.00	70.00	70.00		70.00	70.00	70.00	SMAD pg 571	
S/C Antenna Pointing Error	deg	10.0	10.0	10.0		10.0	10.0	10.0		
S/C Antenna Pointing Error Loss - L_θ	dB	-2.18	-2.18	-2.18		-2.18	-2.18	-2.18		
S/C Antenna Gain - G	dBI	1.07	1.07	1.07		1.07	1.07	1.07		
Transmitter Power	Watts	2	2	2		75	75	75		
Transmitter Power - P	dBW	3.01	3.01	3.01		18.75	18.75	18.75		
Transmitter Line Loss - L_l	dB	-0.5	-0.5	-0.5		-4	-4	-4		
Transmitter Feed Loss - L_a	dB	0.00	0.00	0.00		0.00	0.00	0.00		
Transmitter EIRP	dBW	3.58	3.58	3.58		30.29	30.29	30.29	$EIRP=P+L_l+G_t+L_a$	
Transmission Path Losses - L_a	dB	-0.50	-0.50	-0.50		-0.50	-0.50	-0.50		
Receiver Polarization Loss - L_p	dB	-3	-3	-3		-3	-3	-3		
Receiver Line Loss - L_r	dB	-1	-1	-1		-0.5	-0.5	-0.5		
Receiver Feed Loss - L_a	dB	0.00	0.00	0.00		0.00	0.00	0.00		
Received Carrier Power - C	dBW	-142.08	-134.19	-131.48		-125.81	-117.92	-115.21	$C=EIRP+L_s+L_a+G$	
Total Received Noise Power - N	dB	-156.05	-156.05	-156.05		-150.41	-150.41	-150.41	$N=k*T_s*B$	k=1.38E-23
Received Carrier To Noise Ratio - C/N	dB	13.97	21.86	24.57		24.60	32.49	35.20	SMAD pg 550-556	
Received Energy Per Bit - E_b	dB	-189.68	-181.79	-179.08		-165.63	-157.74	-155.03	$E_b=C/R_s$	
Received Noise Spectral Density - N_o	dB	-209.06	-209.06	-209.06		-203.42	-203.42	-203.42	$N_o=k*T_s$	
Calculated Eb/No	dB	19.37	27.27	29.98		37.78	45.68	48.39		
Eb/No Margine	dB	9.77	17.67	20.38		24.48	32.38	35.09		

Table 6. STARE Operational Link Budget 2012

Group #	Group Name	Total bytes	Storage rate [sec]	Records stored per day	bytes to store/day
0	HEALTH_TLM_t	244	60	1440	351360
1	EPIC_PMAD_SP_TLM_t	172	60	1440	247680
2	GNC_TLM_f01_t	40	60	1440	57600
3	GNC_TLM_f02_t	67	60	1440	96480
4	GNC_TLM_f03_t	36	60	1440	51840
5	GNC_TLM_f04_t	48	60	1440	69120
6	GNC_TLM_f05_t	61	60	1440	87840
7	GNC_TLM_f06_t	58	60	1440	83520
8	GNC_TLM_f07_t	40	60	1440	57600
9	GNC_TLM_f08_t	74	60	1440	106560
10	GNC_TLM_f09_t	63	60	1440	90720
11	GNC_TLM_f10_t	48	60	1440	69120
12	PL_TLM_A_t	15	60	1440	21600
13	PL_TLM_B_t	9	60	1440	12960
14	**PL_TLM_C_t**	STARE Serial Data			**670,880**
15	SV_SUM_TLM_t	66	60	1440	95040
16	Event_Logger_TLM_t	24	60	1440	34560
Total download per day		1065		23040	**2204480**
	Total Bytes to store per day		2.20	MB	

Table 7. TLM data with 10 Observations + 1 Raw Image File Scenario (From O'Brien, 2011)

2. 45 Degree Elevation Angle Access

As shown in Table 1, a 10-degree elevation angle only gives NPS a -12.51 dB Eb/No margin and would be impossible to communicate with STARE with the antennas in the stowed configuration. The best opportunity and the greatest Eb/No margin are produced between a 45-degree and 90-degree elevation angle. Table 8 shows an analysis of accesses with the constraint added.

NPS to STARE (45 degree Elevation Angle)			
Average Duration	115.36	seconds	
Maximum Duration	166.211	seconds	
Minimum Duration	8.036	seconds	
Total Passes for a Year	385	passes	

Table 8. 45 Degree to 90 Degree Elevation Angle Access Analysis

Compared to Table 4, the amount of passes available has decreased significantly along with the average duration of access time, which highlights the necessity of having multiple ground stations. Multiple ground stations increase the opportunities to communicate with STARE. With all ground stations operational, access opportunities to communicate with the STARE CubeSat over a one-year timeframe increase to 1,521 passes. Table 9 shows the access analysis by ground station.

Access Per Ground Station		
AFIT		
Average Duration	116.6125	seconds
Maximun Duration	165.218	seconds
Minimum Duration	15.257	seconds
Total Passes for the Year	403	passes
Mean Elevation Angle	52.12	degrees
SDL		
Average Duration	115.6743	seconds
Maximun Duration	164.302	seconds
Minimum Duration	5.826	seconds
Total Passes for the Year	425	passes
Mean Elevation Angle	51.9	degrees
NPS		
Average Duration	115.3591	seconds
Maximun Duration	166.211	seconds
Minimum Duration	8.036	seconds
Total Passes for the Year	385	passes
Mean Elevation Angle	52	degrees
HSFL		
Average Duration	116.4425	seconds
Maximun Duration	169.437	seconds
Minimum Duration	13.084	seconds
Total Passes for the Year	308	passes
Mean Elevation Angle	52.1	degrees

Table 9. Ground Station 45 Degree Elevation Angle Access Analysis

IV. CONCLUSIONS AND FUTURE WORK

A. ASTRODEV CII RADIO

1. Conclusion

The testing conducted on the AstroDev CII radio shows that it will work as expected and receive commands from the ground station given a successful deployment of the receive antenna. The data rates are sufficient for the overhead time calculated with the passes that the NPS ground station would have available to send commands to STARE.

2. Future Work

A HAB test needs to be conducted using an actual AstroDev CII radio to obtain performance characteristics data at high altitude and a link budget created to analyze the data. This test should be conducted using MC3 to track the AstroDev CII radio to analyze the CII radio characteristics and obtain data for MC3 ground station tracking and signal strength analysis.

Testing of an S band radio should be conducted to see if it would provide better data rates and connectivity that is more reliable than a UHF radio. Tests should be conducted on changing data rates and data file sizes to see if higher data rates could be achieved. HAB tests would need to be conducted, as well as a link budget created. A S-band radio would have to be procured for testing and test procedures would have to be written.

B. STARE ANTENNA

1. Conclusion

With the receive antenna in the stowed configuration, the MC3 ground station will not be able to reliably close the link with STARE. As shown in Table 1, the Eb/No margin is too low at 10 and even 45 degrees. With the spacecraft's receive antenna gain at -36.5 dBm in the stowed configuration, the NPS transmit set does not have the power or the gain to overcome the disadvantage. Using

the same power capability of 75 Watts and a higher gain antenna, such as the 60 ft antenna at SRI, it is possible to gain an advantage over the stowed receive antenna and communicate with the STARE CubeSat. The 90-degree elevation angle increases the Eb/No margin but the overhead pass opportunities at that angle are very few. A successful deployment of the receive antenna is necessary for MC3 to communicate normally with STARE.

2. Future Work

For future iterations of Colony Buses, redundancy options need to be examined for the deployment of antennas. An error function may be needed that will automatically deploy the antennas after launch if a deploy error is triggered by the spacecraft or if communications with the ground station is not established within some reasonable timeframe. Improved testing by the bus developer prior to delivery of the bus may decrease future errors. Testing of a backup burn wire system and an actual deploy test may be necessary to avoid deploy problems on future iterations of the STARE CubeSat.

C. MC3 GROUND STATIONS

1. Conclusion

The four MC3 ground stations have multiple daily pass opportunities to communicate with STARE throughout the year. As shown in Table 7, each ground station over a year's time has numerous passes with a mean elevation angle between 45 and 90 degrees. With a successful deployment of the STARE receive antenna and solar panels, each ground station will have an Eb/No margin high enough to send commands and collect data.

2. Future Work

As with the radio in the spacecraft, new types of transmission and receive equipment need to be explored for the MC3 ground stations. Suggested types of equipment upgrades and enhancements can be found in Phillip B. Ibbitson's thesis entitled "Mobile CubeSat Command And Control Architecture And

CONOPS.” Data rates and frequency changes should be analyzed to see if transmission capabilities could be enhanced. HAB tests should also be conducted with a S band radio to test the MC3 S band antennas’ performance and tracking capabilities. The use of a larger MC3 ground station transmit antenna with a higher gain or a more powerful transmitter radio should be considered as well. A link budget should then be created to examine both possibilities. Future MC3 installation sites need to be analyzed for feasibility, practicality and cost.

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LIST OF REFERENCES

Arnold, S., Johnson, M., & Davis, M. (2011). *CubeSat technologies: MC3 status update* [PowerPoint]. Monterey, CA: Naval Research Laboratories.

AstroDev. (2012). *AstroDev CII radios: Product overview.*

DeJesus, A. C. (2012). *Integration and environmental qualification testing of spacecraft structures in support of the Naval Postgraduate School CubeSat launcher program* (Master's thesis, Naval Postgraduate School).

Griffith, R. C. (2011). *Mobile CubeSat Command And Control (MC3)* (Master's thesis, Naval Postgraduate School).

HQ Air Force Space Command/A3CD. (2007). *Space surveillance network (SSN) site information handbook.*

Ibbitson, P. B. (2012). *Mobile CubeSat command and control architecture and CONOPS* (Master's thesis, Naval Postgraduate School).

Jenkins, R. D. (2010). *NPS-SCAT: Systems engineering and payload subsystem design, integration and testing of NPS' first CubeSat* (Master's thesis, Naval Postgraduate School).

Kelso, T. S. (2009, July 15). Iridium 33/Cosmos 2251 collision. Retrieved from CelesTrak website: http://celestrak.com/events/collision.asp

Kelso, T. S. (2011, May 21). Chinese ASAT test. Retrieved from CelesTrak website: http://celestrak.com/events/asat.asp

Minelli, G. (2012). *Mobile CubeSat command and control (MC3) ground stations* [Power Point]. Monterey, CA: Naval Postgraduate School.

Morrison, G. C. (2011). *Mobile CubeSat command and control: Assembly and lessons learned* (Master's thesis, Naval Postgraduate School).

NanoSat Engineering. (2011). *Colony II bus payload developer guide version 1.2.* Huntington Beach, CA: Boeing.

Naval Research Laboratory. (2011). *Cube sat space/ground interface control document version 2.1.* S.W., Washington, DC: Author.

O'Brien, T. E. (2011). *Space situational awareness CubeSat concept of operations* (Master's thesis, Naval Postgraduate School).

Simms, L., Riot, V., De Vries, W., Olivier, S., Pertica, A, Bauman, B., Phillion, D., & Nikolaev, S. (2011, March 17). *Optical payload for the STARE mission.* LLNL-CONF-474234. Retrieved from Lawrence Livermore National Laboratory website: https://e-reports-ext.llnl.gov/pdf/473852.pdf

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